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13. ABSTRACT *(Maximum 200 words)*

The MATLAB/Simulink analysis tools developed and upgraded by the electrical engineering team were successfully incorporated into the optimization environment. A well posed optimization problem was formulated for a sample system consisting of a filter and converter. It was shown that the solution of the optimzation problem yielded realistic parameter values. Also the existence of suboptimal solutions was investigated. These results are the core results for developing an optimization methodology for the full power distribution system. The optimization methodology is being reworked into a global/local formulation. This formulation allows us to define an optimization problem for the entire power distribution system. A preliminary framework for the sample system has been developed, and the appropriate software is being generated. The global/local formulation has also been applied to the design filters components with the inductors as their local level subcomponents. Preliminary results indicate a significant decrease in computational time while retaining the accuracy of the full problem.

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Global/Local Design Optimization of A Power Distribution System

Final Report

Sponsored By

Air Force Office of Scientific Research

AFOSR Contract Number: F49620-00-1-0056

Project ending date: 11/30/00

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Objectives

Assist in the development of optimization methodologies for the design of next generation power systems. Implement a global/local optimization technique to achieve a cost effective design optimization strategy.

Status of the Effort

During the past year significant progress was made on demonstration of the global/local methodology for minimum weight design of the power electronic circuits.

Accomplishments/New Findings

1. The MATLAB/Simulink analysis tools developed and upgraded by the electrical engineering team were successfully incorporated into the optimization environment.

2. A well-posed optimization problem was formulated for a sample system consisting of a filter and a converter. It was shown that the solution of the optimization problem yielded realistic parameter values. Also the existence of suboptimal solutions was investigated. These results are the core results for developing an optimization methodology for the full power distribution system.

3. The optimization methodology is being reworked into a global/local formulation. This formulation allows us to define an optimization problem for the entire power distribution system. A preliminary framework for the sample system has been developed, and the appropriate software is being generated. The global/local formulation has also been applied to the design filters components with the inductors as their local level subcomponents. Preliminary results indicate a significant decrease in computational time while retaining the accuracy of the full problem.

Personnel Supported

During this period the Principal Investigators received summer salary support as follows.

P.I.	% Of Academic Year	% Of Summer Salary
Z. Gürdal, Professor	-	20%
Scott Ragon, Research Assoc.	20% Calendar Year	

Publications

The following journal article was submitted for publication.

Chandrasekaran, S., S. A. Ragon, D. K. Lindner, Z. Gurdal, and D. Boroyevich, "Optimization of a Power Distribution Subsystem," submitted to AIAA Journal of Aircraft.

The following conference paper has been presented (name of the presenter is highlighted).

Ragon, S. A., S. Chandrasekaran, **Z. Gürdal**, D. K. Lindner, and D. Boroyevich, "Optimal Design of a Power Distribution System," accepted for the 38th AIAA Aerospace Sciences Meeting and Exhibit: Multidisciplinary Design Optimization, Reno, NV, Jan 10 - 13, 2000.

Interactions/Transitions

7a. Participation at meetings, etc

38th AIAA Aerospace Sciences Meeting and Exhibit: Multidisciplinary Design Optimization, Reno, NV, Jan 10 - 13, 2000: Prof Gürdal presented a paper on optimization of the sample system.

Exergy Workshop, AFRL, Dayton, OH, Dec 16, 17, 1999: This workshop was organized by AFRL to explore the possibility of using exergy as a basis for the optimization of various aircraft subsystems. Profs Gürdal and Lindner presented the results on optimization.

Exergy Workshop, Virginia Tech, Blacksburg, VA, March 23-24, 2000: This workshop was a follow-up to the previous Exergy Workshop. Prof. Lindner presented results on the global/local formulation for a power distribution system.

7c. Transitions

Based on the preliminary results for the optimization of the sample system, the Center for Power Electronic Systems (CPES) at Virginia Tech was awarded a contract by Schnieder Electric Company to (in part) develop an optimization tool for the design of a power factor correction circuit. (This circuit is basically a filter followed by a boost converter as in the sample system studied under this project.) Profs. Boroyevich, Gürdal, and Lindner are among the PI's for this project. Mr. M. Arpilliere of Schnieder Electric, S.A. is the Program Manager. The optimization methodology developed under the AFOSR project was extended to the power correction circuit.

Additionally, under the same contract, ADOPTECH Inc, of Blacksburg Virginia initiated a preliminary study for implementation of the Genetic Algorithms for power electronic circuit design. A commercial code capable of handling discrete power electronics problems with specified topology is being developed. An expansion of the capability to design power electronics circuit topologies is envisioned if the theoretical developments from the Virginia Tech team can be realized.

New Discoveries, Inventions, or Patent Disclosures

There were no new disclosures during this period.

Honors/Awards

No honors or awards were accepted during this period.

Global/Local Design Optimization

Introduction

A major goal of the present research project is to develop mathematical optimization methodologies and tools for the design of next generation power systems for aircraft/spacecraft. The design task is quite complex, as power distribution systems consist of many diverse subsystems, each of which are typically governed by complex sets of non-linear equations. The simulation of the global power distribution system involves complicated interactions between the various subsystems that need to be accounted for in the design process. Our earlier work has demonstrated that, even for a very simple two-component circuit design, it is advantageous to optimize the system as a whole rather then optimizing each of the individual components independently.

As more and more components are added to the optimization problem, certain difficulties arise. The optimization algorithm becomes less efficient as the number of design variables and constraints increase, and the computational expense of simulating the response of the overall power system rapidly grows very large. In order to surmount these difficulties, we have formulated a global/local design methodology for the power system design.

In the global/local methodology, the overall design problem is decomposed into two design levels: a global design level and a local design level. At the global design level, the overall system is designed using a set of global design variables. These global variables do not specify the details of each component, but instead describe the effect of each component on the other components in the system. The local design level consists of a number of separate detailed design models of each individual component type. For example, there may be a detailed design model of an input filter, a detailed design model of a DC-DC buck converter, etc. The local design variables specify the details that are neglected at the global level.

The global and local design levels interact with one another through a local design database. Before the system level design process begins, a large number of optimized local designs of each power system component are generated and stored in a design database. Each optimized local design is generated as a function of a set of global parameters such as terminal voltages/currents and input/output impedances. Once the design database has been constructed, it is used by the global optimizer to design the overall power system. At each global design iteration, the global optimizer is able to consult the design database to determine the weight of an optimized component as a function of the globally determined parameters. In this way, the global optimizer can incorporate information about optimized local designs without actually performing a local optimization at each iteration.

A more detailed description of the design formulation of a global/local power distribution system will be presented below. First, however, the basic global/local design methodology will be demonstrated using a simpler power electronics design problem that we refer to as the "global/local inductor design problem".

Global/Local Inductor Design Problem

In this section, the global/local design problem will be demonstrated not for the system level design problem, but for a simpler power electronics design application. This simpler application will enable us to evaluate the process without loosing the generality of it when applied to the overall system design. This application is concerned with the design of the input filter illustrated in Figure 1: the three inductors L_1, L_2, and L_d are designed in detail at the local level, and the filter as a whole is designed at the global level.

In our previous work, all of the design variables describing the filter (see Table 1) were considered simultaneously. Note that a large number of these variables (15 variables out of the 18 in the table) describe physical dimensions and characteristics of the three inductors. For example, the variables n_d, A_{cpd}, C_{wd}, W_{wd}, and l_{gd} all specify the detailed design of inductor L_d.

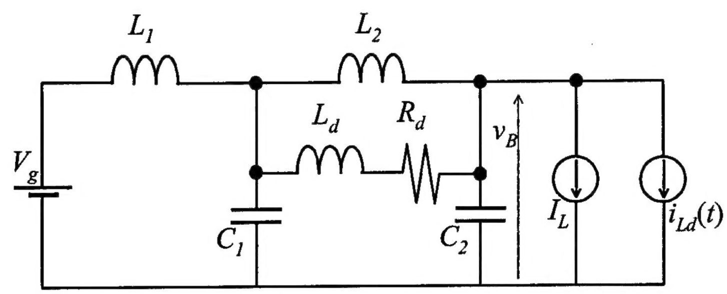

Figure 1 – Input filter schematic

Table 1 – Filter design variables before global/local decomposition

Design Variable	Description
C_1	Filter capacitance
C_2	Filter capacitance
R_d	Filter resistance
n_d	Number of turns for L_d
A_{cpd}	Cross sectional area of winding for L_d
C_{wd}	Center leg width for L_d
W_{wd}	Window width for L_d
l_{gd}	Airgap length for L_d
n_1	Number of turns for L_1
A_{cp1}	Cross sectional area of winding for L_1
C_{w1}	Center leg width for L_1
W_{w1}	Window width for L_1
l_{g1}	Airgap length for L_1
n_2	Number of turns for L_2
A_{cp2}	Cross sectional area of winding for L_2
C_{w2}	Center leg width for L_2
W_{w2}	Window width for L_2
l_{g2}	Airgap length for L_2

If the filter design problem is examined in more detail, it can be seen that the problem naturally lends itself to decomposition into global and local design levels. If we wish to determine the behavior of the filter as a whole, it is not necessary to know the details of each inductor design: we only need to know the inductance, L, of each inductor. This indicates that we may be able to remove the design variables describing the inductor details from the overall (global) design problem. If we wish to compute the total weight of the filter, however, we need to know the weight of each inductor as a function of L. As it turns out, it is possible to formulate a separate local design problem that will allow us to find the minimum inductor weight as a function of the inductance, L, and the peak inductor current, $I_{L(pk)}$. This second optimal design problem will constitute the local design level for the filter design problem, and can be stated as follows:

Local Inductor Design Problem

For specified parameters: L, $I_{L(pk)}$

Minimize: inductor weight

Using variables: n, A_{cp}, C_w, W_w, l_g

Such that:

- The computed inductance:

$$L^{*} = \frac{\mu_o K_1 C_w^2 n^2}{l_g + Z_p/\mu_r},$$

is equal to the given inductance, L. Here, μ_o is the permeability of free space, μ_r is the permeability of ferrite, K_1 is the aspect ratio of the core leg, and Z_p is the mean magnetic path length.

- The widths of the center leg, C_w, and of the window, W_w, are greater than 1 *mm*.
- The copper wire cannot have a cross-sectional area less than $7.29 \times 10^{-8}\ m^2$.
- The current density in the windings of the inductor cannot be greater than maximum allowable current density for copper which was considered to be $5.5 \times 10^6\ A/\text{m}^2$.
- The window of the EE-core houses the windings and the bobbin. The area occupied by the windings is given by:

$$W_a = \frac{nA_{cp}}{F_w},$$

where F_w=0.4 is the window fill factor. The window fill factor is included to account for imperfections in the windings on the bobbin. The area occupied by the bobbin in the window, using simple geometry, can be determined as:

$$W_b = W_{bob} K_2 W_w,$$

where W_{bob} is the thickness of the bobbin wall. Hence, the window is required to be large enough to accommodate the windings and the bobbin. This requirement is formulated as a constraint given by:

$$K_2 W_w^2 > W_a + W_b.$$

- In order to prevent the inductor core from running into saturation, the dimensions of the inductor should be such that the maximum allowable saturation flux density for a ferrite core material, B_{sp} = 0.3 T, is not exceeded. The maximum flux density is determined as the ratio of the maximum flux to the area of cross section of the center leg. Hence, this constraint is given by:

$$B_{sp} > \frac{\Phi_{pk}}{A_{Cw}} = \frac{(\psi_{pk}/n)}{K_1 C_w^2} = \frac{(LI_{L(pk)}/n)}{K_1 C_w^2}.$$

By solving the local inductor design problem, we can compute the minimum inductor weight as a function of L and $I_{L(pk)}$. We can now formulate a design problem for the filter as a whole in which we replace the detailed inductor design variables with the variables L_1, L_2, and L_d. This global level design problem can be stated as follows:

Global Filter Design Problem

Minimize: total filter weight

Using variables: L_1, L_2, L_d, C_1, C_2, R_d

Such that:

- The magnitude of the input-output transfer function of the filter, $A_v(j\omega)$, remains between an upper and lower bound up to a passband edge frequency, ω_p (see Figure 2):

$$-1\ dB \le |A_v(j\omega)| \le 6\ dB \quad \text{for } 0 \le \omega \le \omega_p = 2\pi 5\times10^3 \text{rad/sec.}$$

- The magnitude of the input-output transfer function, $A_v(j\omega)$, remains below an upper bound above a certain frequency, ω_{s1} (see Figure 2):

$$|A_v(j\omega)| < -60\ dB \quad \text{for } \omega > \omega_{s1} = 2\pi\cdot 50\times10^3 \text{rad/sec}$$

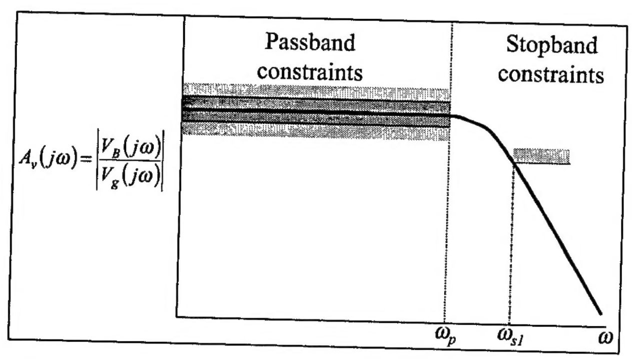

Figure 2 - Definition of frequency domain constraints

- For a given load disturbance, the maximum transient excursion of the output voltage of the filter, Δv_B, is less than 20 V.

- The output impedance of the filter, Z_{of}, which depends on the design parameters, must be less than the input impedance of the converter, Z_{iL}, in order to ensure stability of the interconnected system. Since Z_{iL} is given, sufficient separation between these two impedances can be enforced by requiring that the maximum output impedance of the filter satisfy:

$$Z_{o\_\max} = \max_{\omega}\left(|Z_{oF}(j\omega)|\right) < 15 \text{ dBO} < Z_{iL}.$$

- In order to assure that the interaction between the filter and the power bus is stable, the minimum input impedance of the filter must exceed the maximum output impedance of the power bus, Z_{oC}. Since Z_{oC} is given, sufficient separation between these two impedances can be enforced by requiring that the minimum input impedance of the filter satisfy:

$$Z_{i\_min} = \min_{\omega}\left(\left|Z_{iF}(j\omega)\right|\right) > 3 \text{ dBO} > Z_{oC}.$$

Note that we cannot solve the global design problem independently from the local design problem – we need the local design problem in order to compute the weight of each inductor in the filter. What, then has been gained by decomposing the problem? The answer lies in the concept of the local design database.

Before we begin solving the overall filter design problem, we first solve the local optimization problem for a range of different L and $I_{L(pk)}$ values, and store the results in a local design database. Given the data stored in the database, response surface methodologies are used to construct a simple function (usually a polynomial) that approximates the inductor weight as a function of L and $I_{L(pk)}$.

Once the response surface function is obtained, the overall filter can be designed. Whenever the weight of any of the three inductors is required, the current values of the L and $I_{L(pk)}$ are inserted into the response surface function and the required weight is efficiently computed without the need for optimizing the local component for that combination of the L and $I_{L(pk)}$. Given the existence of the response surface function, the number of design variables in the present filter design problem is reduced from eighteen to six. Likewise, the number of constraints is reduced from twenty (five for each of the three inductors + the five from the filter as a whole) to five. This means that individual filter optimization problems can now be solved more efficiently and reliably. Filter design studies (which may entail solving a large number of filter optimization problems, each corresponding to different operating conditions, etc.) are more efficient as well, as the same local database can be reused for each optimization problem. In fact, the local design database can potentially be reused for any electrical component that contains inductors.

Results

In this section, preliminary results illustrating the global/local inductor design methodology are presented. First, the filter optimization problem was solved without any global/local decomposition. These results are presented in Table 2 (these results differ from those generated and reported earlier in this project because *i-* a different current density for copper was used, *ii-* a slightly more accurate expression for L in terms of the inductor design variable was used). It should be noted that it took a number of different optimization "runs" to obtain these results – the optimization problem was very slow to converge especially with respect to the detailed inductor design variables. The detailed inductor design variables in Table 2 correspond to the final values of L_1=25.6 μH, L_2=283.5 μH, and L_d=17.9 μH.

Next, the local inductor design problem was solved for different combinations of L and $I_{L(pk)}$ and the results were stored in a local design database. A third order polynomial in two dimensions was fit to the data; this polynomial approximates the optimal inductor weight as a function of L and $I_{L(pk)}$. This polynomial was then used in conjunction with the global design problem to generate the optimal filter design shown in Table 3.

These results agree closely with those presented in Table 2, and were obtained with considerably less computational effort. In the near future additional global/local inductor designs will be generated, and the differences in computational effort between the full optimization (no decomposition) and the global/local optimization methodologies will be documented.

Table 2 - Optimal filter design (no decomposition)

Variable Name	Value
C_1	7.82 μF
C_2	31.96 μF
R_d	21.95 μF
n_d	2.47
A_{cpd}	$.940 \times 10^{-6}$ m^2
C_{wd}	$.287 \times 10^{-2}$ m^2
W_{wd}	$.521 \times 10^{-2}$ m^2
l_{gd}	$.504 \times 10^{-3}$ m^2
N_1	3.00
A_{cp1}	$.144 \times 10^{-5}$ m^2
C_{w1}	$.388 \times 10^{-2}$ m^2
W_{w1}	$.679 \times 10^{-2}$ m
l_{g1}	$.953 \times 10^{-3}$ m^2
N_2	8.24
A_{cp2}	$.108 \times 10^{-5}$ m^2
C_{w2}	$.681 \times 10^{-2}$ m^2
W_{w2}	$.941 \times 10^{-2}$ m
l_{g2}	$.200 \times 10^{-2}$ m^2
Weight	0.151 *kg*

Table 3 - Optimal filter design obtained using global/local methodology

Variable Name	Value
C_1	7.79 μF
C_2	30.54 μF
R_d	22.61 μF
L_1	26.15 μH
L_2	277.44 μH
L_d	18.36 μH
weight	0.153 *kg*

Global/Local Formulation for System Level Design

The formulation for the system level global/local design problem, which is one of the primary tasks of this project, is be presented in this section. Here, the global design level will constitute the power system as a whole, and the local design level will include detailed local models of the individual power system components, such as the filter component described above. For purposes of presenting the global/local formulation, we will concentrate on the simplified global system illustrated in Figure 3.

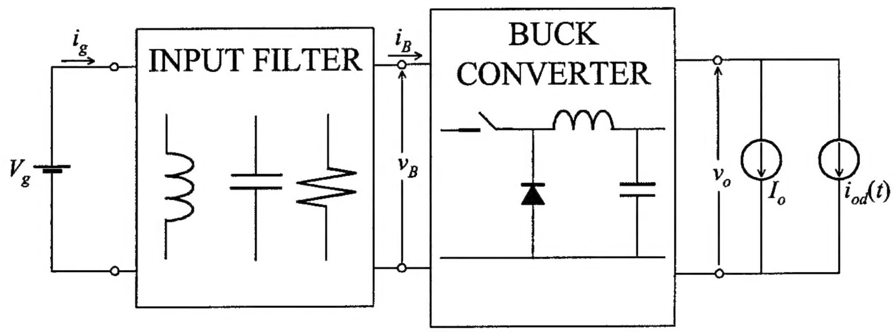

Figure 3 – Block diagram of sample system

Global Level Design

The global/local formulation presented in this section utilizes the model illustrated in Figure 4 for the global level design problem. In this model, each of the local components (in this case, the input filter and the buck converter) is represented using two-port models. In this representation, each component in the power system is characterized by four transfer functions: A_i, A_v, Z_i, *and* Z_o. Depending on the form of each of these functions, any of the components in the power system may be modeled.

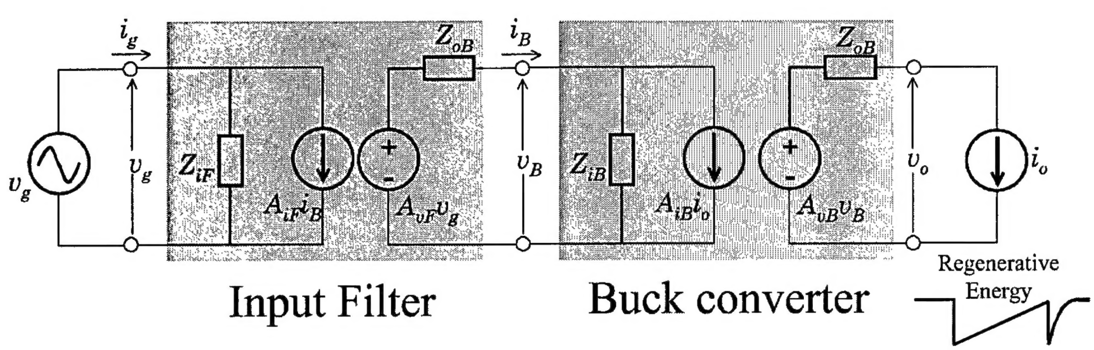

Figure 4 – Global representation of power system

In the case of the input filter, the transfer functions are:

$$A_{vF} = A_{iF} = \frac{1+s/\omega_{aF}}{\Delta(s)}$$

$$Z_{oF} = K_{oF}\frac{1+s/\omega_{zoF}}{\Delta(s)}$$

$$Z_{iF} = K_{ziF}\frac{\Delta(s)}{s(1+s/\omega_{ziF})}$$

$$\Delta(s) = 1+\frac{s}{Q_F\omega_{nF}}+\frac{s^2}{\omega_{nF}^2},$$

and therefore the global design variables consist of the parameters K_{oF}, K_{ziF}, ω_{aF}, ω_{zoF}, ω_{ziF}, ω_{ziF}, and Q_F. In the case of the buck converter, the transfer functions are:

$$A_{vB} = K_{vB}\frac{1+s/\omega_{avB}}{\Delta(s)}$$

$$A_{iB} = \frac{P_o}{V_g}\frac{1+s/\omega_{aiB}}{\Delta(s)}$$

$$Z_{oB} = K_{oB}\frac{1+s/\omega_{zoB}}{\Delta(s)}$$

$$Z_{iB} = -\frac{V_g^2}{P_o}\frac{\Delta(s)}{1+s/\omega_{ziB}}$$

$$\Delta(s) = 1+\frac{s}{Q_B\omega_{nB}}+\frac{s^2}{\omega_{nB}^2}.$$

and the global design variables are the parameters K_{vB}, K_{oB}, ω_{aiB}, ω_{avB}, ω_{zoB}, ω_{ziB}, ω_{nB}, and Q_B. The two-port global models will be capable of accurately predicting the low frequency behavior of the power system, including the interface voltages v_B and v_o. Global constraints will include upper bounds on these voltages:

$$\Delta v_o \le \Delta v_{o,\max}$$

$$\Delta v_B \le \Delta v_{B,\max}.$$

In addition, the stability of the interconnected system will be assured by imposing a constraint on the input impedance of the converter and the output voltage of the filter:

$$\min_{\omega}\left(\|Z_{iB}\| - \|Z_{oF}\|\right) \le Z_{\max}.$$

Local Level Design

The input filter local model (Figure 1) and the buck converter local model (Figure 5) are the same as those used in our previous optimization work. The objective of the local level design problems will be to minimize the component weight. The local design variables for the filter were listed in Table 1, and the local design variables for the buck converter are listed in Table 4.

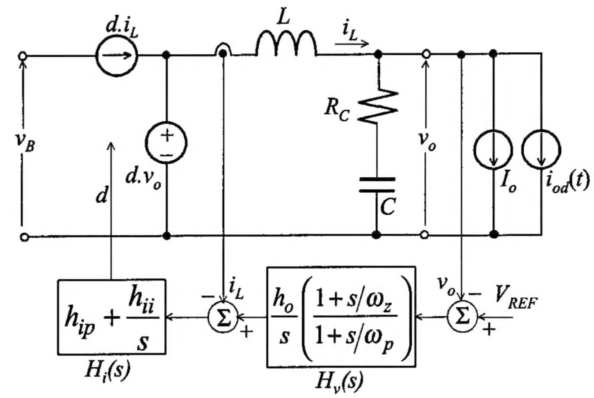

Figure 5 – Buck converter model

Most of the constraints imposed on the local level design problems are identical to those used in our previous work. Constraints imposed on the filter at the local level include frequency domain constraints on the input-output transfer function (passband and stopband constraints), and physical constraints governing the design of the inductors. Local buck converter constraints include frequency domain constraints on the audiosusceptibility of the converter and the crossover frequency of the voltage loop gain. Constraints will be imposed to guarantee the internal stability of the converter, and the physical constraints governing the inductor design will be enforced.

In addition to these performance and stability constraints, we will require that the local level filter or converter design match the behavior of the corresponding global level design up to a specified frequency. This will be accomplished by matching the higher order local level transfer function with the lower order global level transfer function as closely as possible up to this frequency.

Table 4 – Design variables for buck converter

Design Variable	Description
N	Number of turns for L
A_{cp}	CSA of winding for L
C_w	Center leg width for L
W_w	Window width for L
l_g	Airgap length for L
C	Capacitance
f_s	Switching frequency of buck converter
h_o	Voltage controller gain
ω_z	Voltage controller zero
ω_p	Voltage controller pole
h_{ip}	Current controller proportional gain
h_{ii}	Current controller integral gain

For the system level design problem, a different local design database will be constructed for each different component type in the system. In the present case, one local design database will be developed for the filter, and a second database will be developed for the converter. Each database will consist of number of optimized local designs, each of which corresponds to different combinations of the global design variables. The local filter database will be constructed as a function of the global filter design variables, and the local converter database will be constructed as a function of the global converter design variables.

Once these databases are constructed, response surface methodologies will be utilized to construct functional approximations to the minimum weight of each component as a function of the global design variables. Once these functions are developed, it will be possible to optimize the interconnected system in an efficient manner. For any combination of the global design variables, these functions will return the minimum weight of the local component that satisfies all local constraints. The result of the converged optimization process will be a minimum weight system that satisfies all global and local constraints. We will continue this research by developing local design databases for both the filter and converter. The global/local methodology will then be demonstrated on the sample filter-buck converter system.

In addition, the local level design optimization problems proved to be mixed discrete continuous optimization problems with predefined set of gage dimensions (such as the wire dimensions), off-the shelve component selection (such as resistors and capacitors), and multiple discrete choices (such as the core types and core material selection for the inductor component, and different component types). Such problems require special algorithms, such as the genetic algorithms, to be adapted to the power circuit design optimization. Finally, some of the local component topologies, such as the filter topology, may need to be included into the design optimization problem. Such an approach will again require a powerful search scheme capable of sifting through various topologies to find an optimal solution. An extension of this work would be to design local topologies within the framework of global/local design methodology by using genetic algorithms.